An Examination for Increasing the Motor Constant of a Cylindrical Moving Magnet-Type Linear Actuator

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This paper describes the motor constant of a cylindrical moving magnet-type linear actuator for obtaining high response characteristics. The theoretical expression of motor constant square density *G* is deduced using the permeance method. A prototype linear actuator is designed in both permeance method and the finite element method. Measured motor constant and motor constant square density of the prototype linear actuator are 17.1 $\mathrm{N^2/(Wm^3)}$ and $2.6 \times 10^6 \mathrm{N^2/(Wm^3)}$ respectively, where these values are over twice as large as those of conventional linear motors.

***Index Terms*—Finite element method (FEM), linear actuator, motor constant, motor constant square density, permanent magnet, permeance method.**

I. Introduction

LARGE motor constant is essential for linear actuators (LAs) used in factory automation equipment to minimize the motor size and improve its respondency [1], [2]. This paper compares the motor constant between a prototype LA and conventional linear motors. The prototype LA is designed by using the permeance method and the finite element method [(FEM): Maxwell 2D Ver. 8, Ansoft Co., Ltd.] in order to satisfy these demands.

II. Structure of a Moving Magnet-Type LA

Fig. 1 shows the basic structure of a moving magnet-type LA. The LA is composed of yokes, permanent magnets (Nd–Fe–B) and a coil. An LA with dimensions of a diameter of 53 mm and a length of 50 mm is used to examine the motor constant. The pure iron is used for a yoke with its length of the gap δ is 0.3 mm, slot open width s is 3 mm, taper angle α is 45°, taper height h is 0.5 mm and thickness of the bobbin is 1 mm.

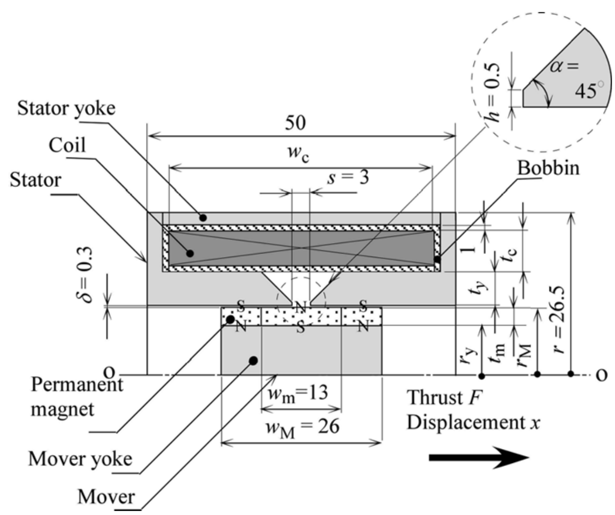

Fig. 1. Basic structure of a cylindrical moving magnet-type LA (unit: millimeters).

III. Derivation of The Motor Constant Square Density

A. Derivation of the Theoretical Expression

Fig. 2 shows the permeance model in the LA [3]. The magnetic resistance R_1–R_9 in the gap are shown in Fig. 2, R_{m1}–R_{m6} are the inside magnetic resistance of the permanent magnets. Fig. 3 shows the magnetic equivalent circuit of the moving magnet-type LA. Magnetic flux $\Phi_1 - \Phi_6$ flows through R_1–R_6 respectively. F_m is the magnetomotive force of the permanent magnets NI is the magnetomotive force by the coil current. The static thrust is calculated by using the permeance method with following assumptions.

1) The permeability of the yoke is regarded as infinity.
2) The effect of the magnetic saturation in the yoke is disregarded.
3) The leakage flux is disregarded.

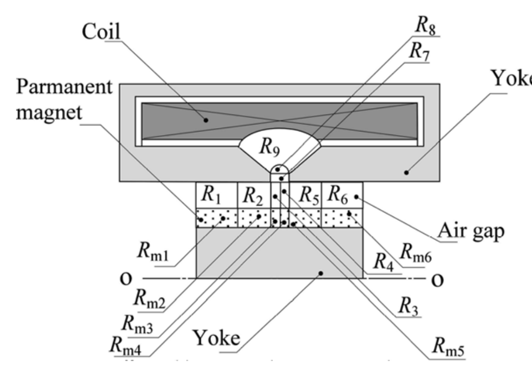

Fig. 2. Permeance model in the moving magnet-type LA.

Magnetic energy W_m and static thrust F are expressed respectively as follows using the magnetic resistance R_1–R_6 and

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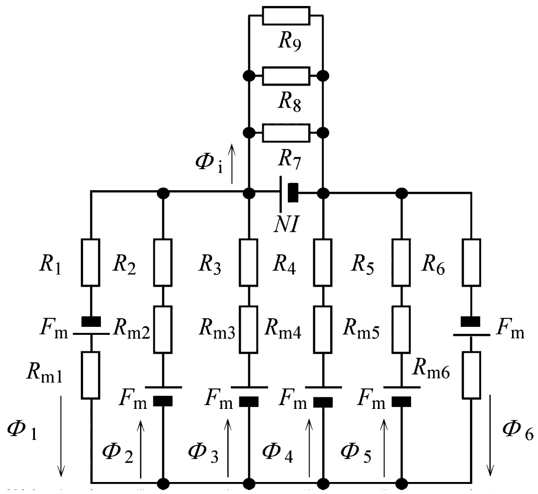

Fig. 3. Magnetic equivalent circuit of the moving magnet-type LA.

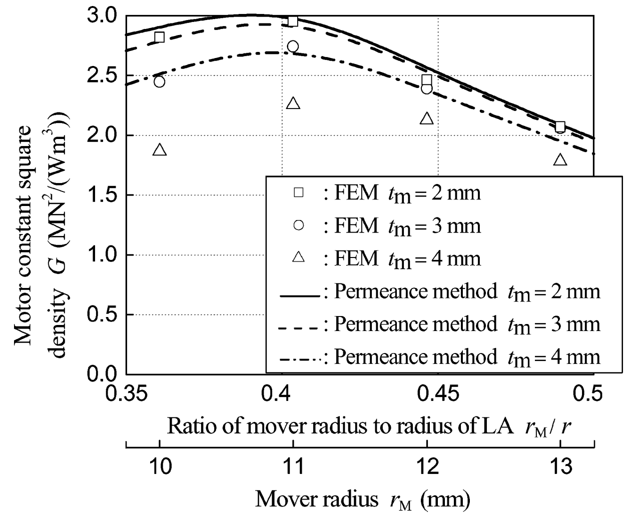

Fig. 4. Motor constant square density dependence with the mover radius as the parameter of permanent magnet thickness in both permeance method and FEM ($NI = 500$ A).

the magnetic flux $\Phi_1 - \Phi_6$.

$$
\begin{aligned}
W_{\rm m} = & \frac{1}{2}\Phi_1^2(R_1 + R_{\rm m1}) + \frac{1}{2}\Phi_2^2(R_2(x) + R_{\rm m2}(x)) \\
& + \frac{1}{2}\Phi_3^2(R_3 + R_{\rm m3}) + \frac{1}{2}\Phi_4^2(R_4 + R_{\rm m4}) \\
& + \frac{1}{2}\Phi_5^2(R_5(x) + R_{\rm m5}(x)) + \frac{1}{2}\Phi_6^2(R_6 + R_{\rm m6}) \\
& + \frac{1}{2}\frac{(NI)^2(R_7R_8 + R_8R_9 + R_7R_9)}{R_7R_8R_9}(\text{J}) \qquad (1)
\end{aligned}
$$

$$
\begin{aligned}
F = & \frac{\partial W_{\rm m}}{\partial x} \\
= & \frac{2\pi\mu_r\mu_0\{2H_{\rm c}t_{\rm m}(1 - w_{\rm m}/w_{\rm m}) - NIx\}NI}{[\ln(1 + t_{\rm m}/r_{\rm y}) + \mu_r \ln\{1 + \delta/(r_{\rm y} + t_{\rm m})\}]}(\text{N}) \quad (2)
\end{aligned}
$$

where $\mu_{\rm r}$ is the recoil relative permeability, μ_0 is the vacuum permeability (H/m), $w_{\rm c}$ is the width of the coil (m), $H_{\rm c}$ is the coercive force (A/m), $t_{\rm m}$ is the thickness of the permanent magnet (m), $w_{\rm m}$ is the length of the mover (m), $w_{\rm M}$ is the length of the permanent magnet (m), x is the displacement (m) and $r_{\rm y}$ is the radius of the mover yoke (mm).

Equation (2) indicates that parameters such as $w_{\rm m}/w_{\rm M}, t_{\rm m}/r_{\rm y}$ and $\delta(r_{\rm y} + t_{\rm m})$ must be reduce in order to increase the static thrust [4]. The permeance method makes it easier to understand the effect of each dimension on the static thrust. The calculation is made under the assumption that there is no magnetic saturation in the yoke. At this point, the dimension of the stator yoke was decided in order to become the magnetic flux density in the stator yoke of the $B_{\rm y} = 1.2$ T. Magnetic flux density $B_{\rm y}$ and magnetic flux $\Phi_{\rm i}$ of the slot open width are given by

$$
B_{\rm y} = \frac{\Phi_1 + \Phi_2 + \Phi_3 + \Phi_{\rm i}}{\pi\{(r_{\rm y} + t_{\rm m} + \delta + t_{\rm y})^2 - (r_{\rm y} + t_{\rm m} + \delta)^2\}}\ (\text{T}) \quad (3)
$$

$$
\Phi_{\rm i} = NI\frac{R_7R_8 + R_8R_9 + R_9R_7}{R_7R_8R_9}\ (\text{Wb}) \qquad (4)
$$

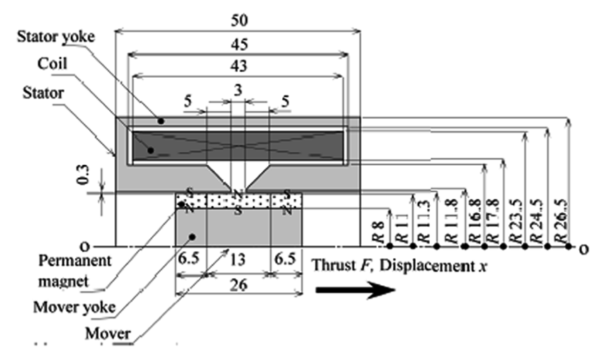

Fig. 5. Basic structure of the moving magnet-type prototype LA (unit: millimeters).

The resistance R and copper loss $w_{\rm c}$ are derived as follows [4]:

$$
R = \rho\zeta\frac{w_{\rm c}t_{\rm c}l_{\rm c}}{\pi^2(d/2)^4}(\Omega) \qquad (5)
$$

$$
\begin{aligned}
W_{\rm c} = & RI^2 \\
= & \rho\zeta\frac{w_{\rm c}t_{\rm c}l_{\rm c}}{\pi^2(d/2)^4}I^2(\text{W}) \qquad (6)
\end{aligned}
$$

where ρ is the copper resistivity (Ωm), ζ is the space factor ($= 0.8$), $w_{\rm c}$ is the axial length of the coil (m), $t_{\rm c}$ is the thickness of the coil (mm), l_c is the average length per coil of the copper wire (m) and d is the conductorial diameter (m).

Motor constant $K_{\rm m}$ of LA is defined as follows:

$$
K_{\rm m} = \frac{F}{\sqrt{W_{\rm c}}}(\text{N}/\sqrt{\text{W}}). \qquad (7)
$$

LAs with large dimensions have generally a large motor constant. Then, The motor constant square density G is compared between the LA and conventional linear motors with different dimensions, where G is the square of the motor constant $K_{\rm m}$

TABLE I
COMPARISON OF THE MOTOR CONSTANT AND MOTOR CONSTANT SQUARE DENSITY BETWEEN THE TRIAL LA AND PM-TYPE LDMS

Item	Symbol	Prototype LA	PM type LDM	Unit
Motor volume	V	1.1×10^{-4}	1×10^{-5} – 1×10^{-3}	m^3
Motor constant	K_m	17.1	0.1 – 70	$N/\sqrt{W}$
Motor constant square density	$G(=K_m^2/V)$	2.6×10^{6}	1×10^{2} – 1×10^{6}	$N^2/(Wm^3)$

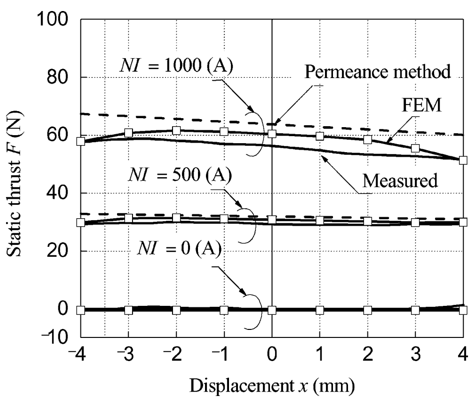

Fig. 6. Static thrust versus displacement characteristics of the moving magnet type LA.

divided by volume V motor constant square density G is given by

$$G=\frac{K_m^2}{V}=\frac{4\pi^2\mu_r^2\mu_0^2\zeta w_c t_c\{2H_c t_m(w_m-w_m)-NIx\}^2}{\rho l_c w_m^2 V[\ln(1+t_m/r_y)+\mu_r\ln\{1+\delta/(r_y+t_m)\}]} \quad (N^2/(Wm^3)) \tag{8}$$

B. Comparison of the Motor Constant Square Density

Fig. 4 shows the motor constant square density dependence with the mover radius as the parameter of permanent magnet thickness in both permeance method and FEM. The motor constant square density G becomes maximum in case that the ratio r_M/r of mover radius r_M to the radius r of LA is 0.4 ($r_m = 11$ mm) and the thickness of the permanent magnets t_m is 2 mm.

IV. Comparison of the Motor Constant

Fig. 5 shows the basic structure of a moving magnet-type prototype LA. Referring to the calculated results shown in Fig. 4, 3 mm for the permanent magnets thickness t_m and 11 mm for the mover radius r_M were given as the optimum value set. These optimum values are also supported from the view point of the armature reaction of permanent magnets.

Fig. 6 shows the static thrust versus displacement characteristics of the LA. Maximum computation errors in permeance method and FEM were 11% and 7% respectively in comparison with measured values. It is assumed that the static thrust drop seen in the measurement at the right shoulder is due to the magnetic saturation in the yoke at a high current of $NI = 1000$ A.

Table I compares the motor constant K_m and the motor constant square density G between the prototype LA and conventional moving magnet-type linear DC motors (PM-type LDMs) [5]. Motor constant square density G of the LA gives 2.6×10^6 $N^2/(Wm^3)$ that is over twice as large as that of conventional PM-type LDMs.

V. Conclusion

This paper characterized the motor constant and motor constant square density of the cylindrical moving magnet LA. The following results were obtained.

1) The theoretical expression of the motor constant square density G was deduced using the permeance method. This expression gave an effective guideline for designing devices and understanding theoretical aspect of moving magnet-type LAs.
2) The motor constant square density G became maximum in case that the ratio r_M/r was 0.4 and t_m was 2 mm.
3) Motor constant square density G of the prototype LA gave 2.6×10^6 $N^2/(Wm^3)$ that was over twice as large as that of conventional PM-type LDMs.

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